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# STUDIES OF THE EQUATORIAL ANOMALY IN THE F-REGION AND THE UPPER IONOSPHERE WITH SPHERICAL ION TRAPS ON THE INTERCOSMOS-2 SATELLITE

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D. Samardzhiev, and K. Serafimov

Translation of "Izsledvaniya na ekvatorialnata anomaliya v oblastta F i vunshnata ionosfera s pomoshchta na sferichni ionni uloviteli, postaveni na sputnika 'Interkosmos-2', Izvestiya Bulgarska Akademiya na Naukite, Geofizichi Institut, vol. 19, 1974, pp. 71-83.

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16. Abstract

The apparatus used and data processing method are described. Data are presented and discussed, indicating the presence of minima at the geomagnetic equator at 400 km altitude, mainly within ±5° of the equator. There are two maxima, mainly between 5 and 15° south and north of the geomagnetic equator, at altitudes of under 500 km. Night minima are indicated close to the geomagnetic equator above 900 km, with maximum geomagnetic control between 1050-1150 km. Some solar radiation influence on the equatorial anomaly is indicated.

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# STUDIES OF THE EQUATORIAL ANOMALY IN THE F-REGION AND THE UPPER IONOSPHERE WITH SPHERICAL ION TRAPS ON THE INTERCOSMOS-2 SATELLITE

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## INTRODUCTION

A characteristic feature of the latitude distribution of the day and night values of electron concentrations in the F region is a distribution, with two maxima at geomagnetic latitudes ~15°-30°N and 15°-30°S and a minimum at about the magnetic equator. A change in distribution is observed at night, with a maximum around the magnetic equator; in years of maximum solar activity, there is no such distribution at night. The existence of the equatorial anomaly was first determined by Appleton in the 1940s [1]. Morphological information on the anomaly, data on its development and conditions for existence and disappearance can be found in [1-8]. A theoretical explanation of the equatorial anomaly is examined in [9-16]. The possibility of study of the equatorial ionization and planetary distribution of electron and ion concentrations by satellite has permitted much data to be obtained on vertical movement of this anomaly, the daily and seasonal changes, and also the effect of solar radiation on the equatorial "valley." Correlation of the results of these experiments and a survey of modern theory are given in [17-21]. Although a multitude of results has already been published, nevertheless, at the present stage, the basic morphological patterns of the unsounded part of the F region, located above the electron concentration maximum, has not been clarified. In particular, according to various studies, no equatorial decrease in electron and ion concentration has been observed above 500 km [17], but it has been asserted in other works that the anomaly should be /71*

*Numbers in the margin indicate pagination in the foreign text.

observed up to 700 km [19]. There are individual results, indicating the presence of the equatorial anomaly at altitudes up to 900 km. The change in maximum and minimum electron concentrations, as a function of geomagnetic latitude, also requires further study. /72
Information on the shift of the "ridge" to the equator in the evening hours and of formation of the "ridge" after sunrise is quite vague and even contradictory (see, for example, [18] and [19]). At present, there is no information on the longitude effect in development of the anomaly. Also, the effect of solar activity on the anomalous phenomenon in the unsounded region has not been analyzed; the effect of various ion components on processes leading to formation of the anomaly is unknown, etc.

This is why the task of the present study is based on data from ion traps, installed in a satellite in an appropriate orbit, to obtain new information on the equatorial anomaly and to elucidate the possibilities of investigating it by the sounding method. The Interkosmos-2 satellite was used for this purpose (it was injected into orbit on 25 December 1969; see [22] for details). Together with other scientific instruments, two spherical ion traps, on rods about 50 cm long, were installed on this satellite.

## METHOD OF MEASUREMENT AND USE OF APPARATUS

Measurements of the concentrations of positive ions, using the spherical ion traps, have been carried out since 1958. The first five such instruments were installed in three artificial earth satellites [23], injected into orbit on 15 May 1958; however, the physical basis and design of the experiment in these satellites was reported much earlier [24]. The experiment with the spherical ion trap was continued in Kosmos-2 [25, 26], launched on 6 April 1962. A spherical ion trap also was used in the Anglo-American satellite Ariel-1, injected into orbit on 26 April 1962 [27,28]; it operated as a mass spectrometer. A similar apparatus was used in Explorer-31 [29], injected into orbit on 29 November 1965.

A spherical ion trap has been installed in rockets. A theory /73
was developed in [30], for application to research rockets (giving the positive ion temperature). The results of measurement of the ion concentration at altitudes up to 1900 km, using the spherical ion traps installed on a Blue Scout rocket, launched on 12 April 1961, are presented in [31]. The theory of the spherical ion trap is also reported in [32-34].

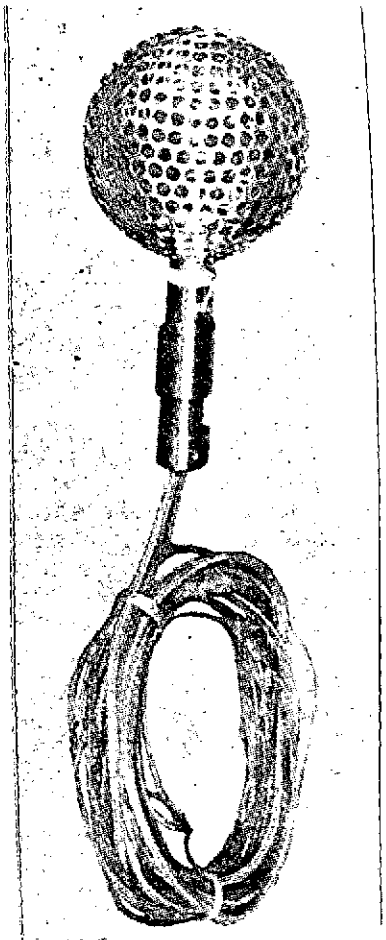

Fig. 1

The spherical ion traps used on Interkosmos-2 (the external appearance of which is shown in Fig. 1) has three electrodes, outer grid, inner (anti-photoelectron) grid and collector.

A train of saw-tooth voltages /74
(see Fig. 2), changing over the range from -5 to -12.5V in 5.8 sec, is supplied to the outer grid of the trap. This train makes for great stability of the potential on the satellite hull [22]. The outer grids of the amplifier have a -95V potential, relative to the hull and -82V, relative to the collector which ensures delivery of the photoemission of the collector. By means of a 13V voltage source, the collector is connected to the input of the direct current amplifier. Moreover, a -13V negative voltage relative to the hull, is established on the collector. A block diagram of the trap and amplifier switching is shown in Fig. 3.

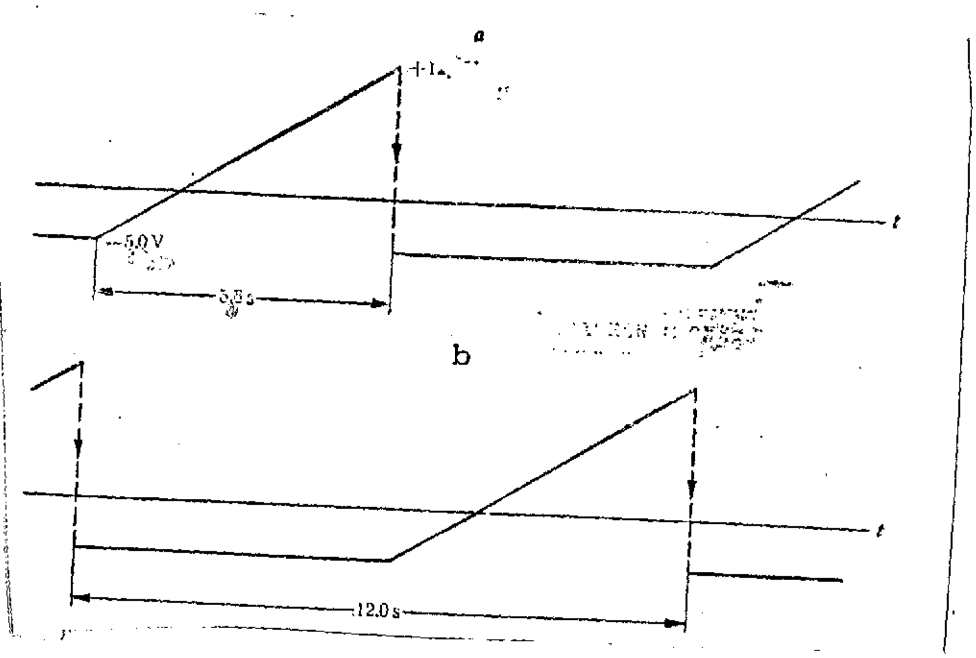


Fig. 2

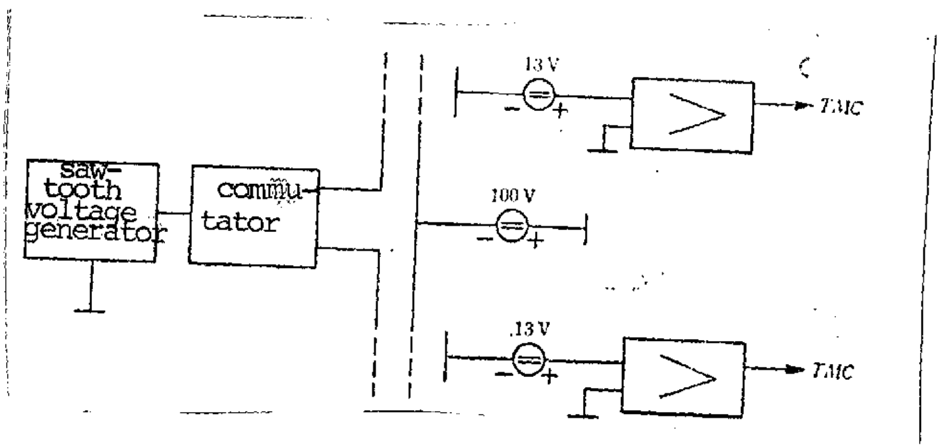


Fig. 3

The outside diameter of the spherical trap is 6 cm, and the effective transmission factor (from the outer to the inner grid) is 0.53. The direct current amplifier, made by a differential scheme with a 2-scale terminal, permits recording the current from the ion trap in the 0.005-2.5 μA range. Upon detecting a voltage in the saw-tooth cycle at the outlet of the collector amplifier circuit, it sends a square marker pulse, the trailing front of which corresponds to the beginning of the rising section of the saw-tooth voltage. With reference to this, the electronic apparatus of the spherical ion trap functions, either in the direct transmission mode or in the mode, remembering the information for one orbit of the satellite.

## METHOD OF PROCESSING EXPERIMENTAL DATA

By means of the radiotelemetry system (TMC), the value of the output voltage of the direct current amplifier on the fine and coarse scales, as well as the instantaneous saw-tooth voltage, were transmitted to earth. Since the traps were continually approximately diametrically opposite the point of the geometric center of the satellite, one was always outside the region of the ion shadow created by the satellite. In that way, the readings of the trap lying outside the shadow region were used in processing.

In the first stage of processing, a current-voltage curve is plotted, i.e., collector current $I_c$ of the trap vs. the instantaneous value of U on the saw-tooth voltage on its outer grid. As was shown in [23], the current-voltage curve of the spherical ion trap has to have a linear section, with angular coefficient

$$\frac{dI_c}{dU} = -\frac{2aSe^2}{m_i V_s} n_i,$$

where a is the effective transmission factor of the trap grids, S is the central cross section of the trap, e is the charge of an electron, $m_i$ is the mass of an ion, $V_s$ is the forward velocity of the satellite, $n_i$ is the positive ion concentration (singly ionized). From this, we obtain

$$n_i = \frac{m_i V_s}{2aSe^2}\left|\frac{dI_c}{dU}\right| \qquad (1)$$

According to [23], the projection of the linear section of the current-voltage curve to the U axis must be of length $\Delta U$, exceeding the stopping potential of the ion: /75

$$\phi_T = \frac{m_1 V_s^2}{2e} . \qquad (2)$$

By analyzing the shape of the current-voltage curve obtained from a given satellite, it has been shown that the actual curve has a reduced linear section, which frequently satisfies the condition $\Delta U < \phi_T$. The cause of this situation is to be sought in a small reduction, in this experiment, of the potential of the collector relative to the satellite hull.

Laboratory tests of a spherical ion trap of a given type, carried out in a vacuum chamber, with irradiation with a flux of positive ions, show that the linear sections of the current-voltage curves is diminished, as a consequence of the absence of full absorption of the ions by the trap, with a decrease in absolute value of the collector potential and an energy exceeding 2.4eV. However, the laboratory studies also confirm that this angular coefficient of the linear section of the curve does not change. This permitted the concentration-mass ratio of a single component medium to be determined quite accurately and, with the existence of two linear sections on the current-voltage curve, the ratio of the second type of ion (in a two-component medium) also disappeared. On the other hand, the difference between the stopping potentials of ions with two different masses made it possible to measure the difference in mass of these ions.

## BASIC RESULTS OF EXPERIMENT

In determination of the singularities of the planetary distribution of the ion concentration in the F region, data of the period from 30 December 1969 to 20 January 1970 were used.

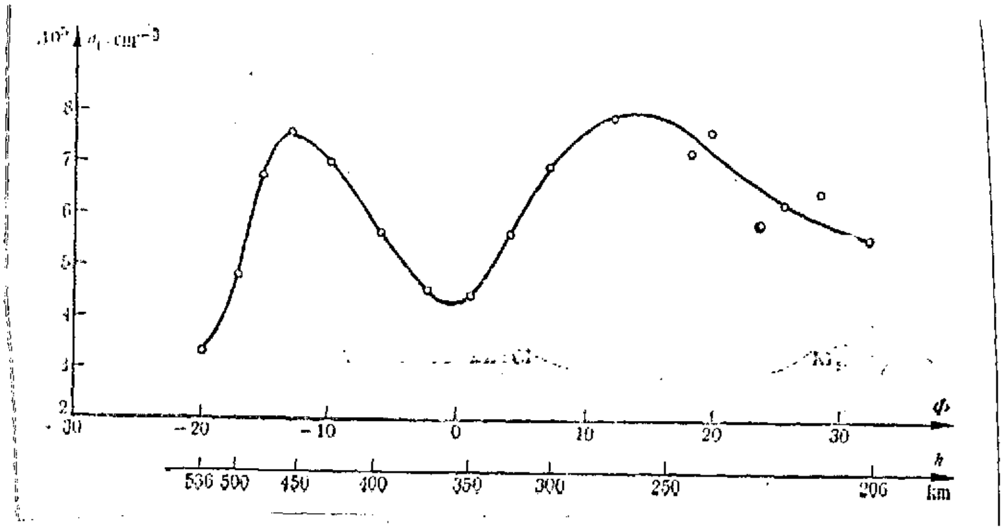

Fig. 4

As an example, the change in ion concentration, measured in the 72nd orbit on 30 December 1969, is shown in Fig. 4. The geomagnetic latitude (limited to the range of usual observation of the equatorial anomaly) and the corresponding altitudes of the satellite are plotted on the abscissa. The "geomagnetic control" of the ion concentration distribution is clearly visible; it led to formation of a minimum around the geomagnetic equator and the appearance of two maxima (the first in the Southern Hemisphere, at about 13° geomagnetic latitude, and the second in the Northern, at about 14° north geomagnetic latitude). The northern maximum is located in the vicinity of the maximum of the F region, which, according to analysis of the N(h) profiles, from data of a series of eastern European stations in December 1969, usually appeared at an altitude of 270-350 km. Analysis of this and many other cases has shown that the position of the maximum depends little on the altitude distribution of the ions, but is determined mainly by the effect of the geomagnetic latitude. The minimum altitude was obtained around the maximum in the F region, and the southern altitude maximum was about 450 km, at which the concentration of charged particles already had to be reduced, showing that, at this geomagnetic latitude, the $n_1$ distribution was determined by the geomagnetic field. The values of $n_1$ in Fig. 4 were obtained from the current-voltage curve, indicating the existence of a single-component ionic composition, which could be identified with ions of atomic oxygen. The predominant effect of atomic oxygen, in examining the height range, confirmed the presence of only one linear section in the current-voltage curve, as in data in the literature [17-24]. /76

The numerous results of different transits of the satellite confirm the example of Fig. 4, definitely with the minimum and maximum approximately coinciding with the geomagnetic latitude. The percent distribution of the minimum during the illuminated period of the day, as a function of geomagnetic latitude, is given in Fig. 5. It is clear from the histogram that 47% of all minima are found in a latitude of ±5% around the geomagnetic equator. In this case, 38% of the cases coincide precisely with the geomagnetic equator. In the north geomagnetic direction, the deviation of the minimum from the geomagnetic equator does not exceed 15°, but it reaches 25° in the south. The minima in the Southern Hemisphere have a greater dispersion from the geomagnetic equator than in the Northern Hemisphere. The fact that every daily minimum appears at an altitude of less than 400 km is interesting. The correspondence of the altitude locations to the minima is shown in Fig. 6. The altitude of the section, through which the satellite passed in the case being analyzed, in the ±30° geomagnetic latitude region, is shown under the histogram. The percentage of the total number of minima on the ordinate, is shown with a dashed line, and the relative number of cases of appearance of daytime minima to the total number of transits analyzed is shown with a continuous line.

The locations of the maxima relative to the geomagnetic equator are shown in Fig. 7. It is seen from the histogram that the probability of appearance of the maximum in the 5-15° range north and south of the geomagnetic equator is predominant. The positions /77 of the maxima to the south have little dispersion, and they reach 30° geomagnetic latitude. All of the northern maxima are located at latitudes from 5 to 15°, and the ion concentration $n_1$ usually is greater than in the south. All maxima of a single-component ionic medium are found under 500 km (see histogram in Fig. 8, for altitude distribution of daily maxima). In this case, the predominant spread of maxima is observed between 200-300 km altitude (around the satellite perigee and in the region directly under the maximum electron concentration in the F region).

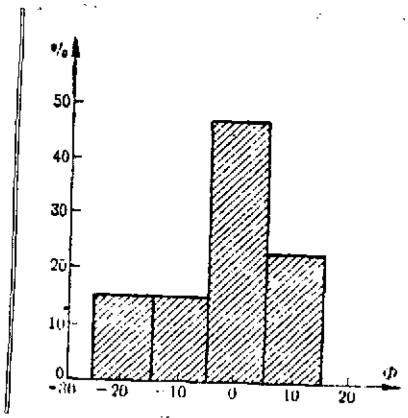


Fig. 5

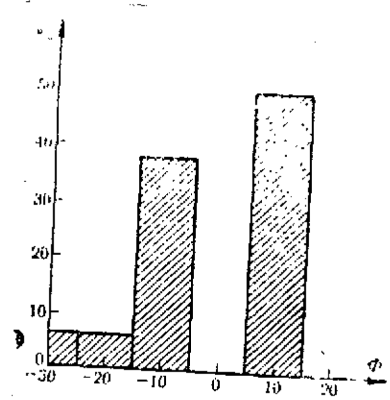


Fig. 7

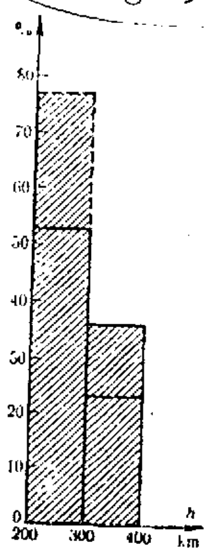


Fig. 6

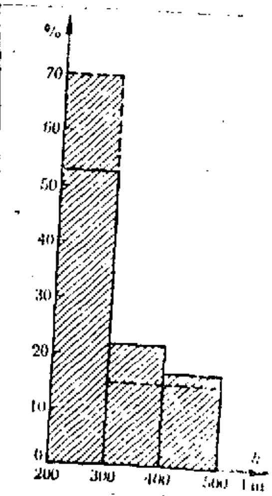


Fig. 8

This establishes the possibility of a conclusive interpretation of the altitude trend in appearance of $n_i$ maxima, connected with the geomagnetic control; in Fig. 8, a histogram of the case /78
of appearance of these $n_i$ maxima, with respect to the total spread of the satellite passages in a given altitude range analyzed is given with solid lines, and with dashed lines, the distribution of the minima relative to the total number of them. On the basis of this histogram, it can be conclusively stated that, at least, the satellite passages through altitudes of 500-590 km and 725-900 km (concerning the ±30° geomagnetic latitude range) do not observe ion concentration maxima. It follows from this conclusion and the results of analysis of Fig. 6 that the equatorial anomaly, in a consideration by seasons, cycles and daily conditions, is limited to the region between 200 and 500 km.

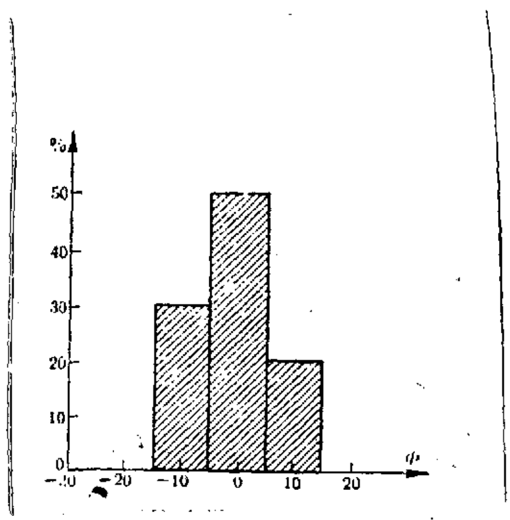


Fig. 9

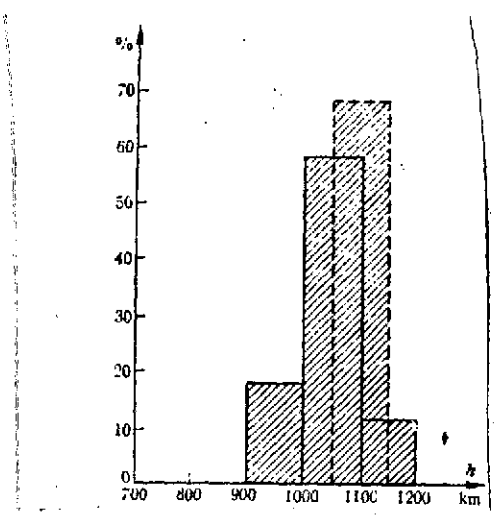


Fig. 10

At night, at relatively low altitudes (up to 900 km), no regularities in geomagnetic distribution of the ion concentrations are observed; at these altitudes, the night-time distribution of $n_i$ in the ±30° geomagnetic latitudes has no sufficiently clear expression of maxima and minima. However, a distinct geomagnetic variation in

$n_1$ is observed above 900 km at night, which is characterized by a deep minimum around the geomagnetic equator. The appearance of minima and maxima at night above 900 km in this range of geomagnetic latitude is revealed by analysis of the current-voltage curves with two linear sections. This fact can be interpreted, from the appearance of a point of existence of two ion components with commensurable concentrations. Analysis of the mass and pattern of this phenomenon will be the object of another work. The percentage distribution vs. geomagnetic latitude, of the number of appearances of minima of $n_1$ of the heavy ion component relative to the total number of minima observed is shown in Fig. 9. It is seen from the histogram that about 50% of the observed minima are located in the ±5° latitude section around the geomagnetic equator. There is, as in other curves, some deviation from the geomagnetic equator to the south (about 30% of the cases are observed in the range of -5 /79 to -15° and only 20% of the minima in the +5 to +15° section). These asymmetries can also be found in Figs. 5 and 7, on the daytime curves of the equatorial anomaly.

The altitude distribution of the night-time minima in ion concentration, relative to the total number of transits analyzed, is shown in Fig. 10. It is clear from it that the geomagnetic effect on a two-component ionic medium appears strongly in the 1000-1100 km range. The maxima of this equatorial magnetic effect is observed in the 1050-1150 km range (see dashed line in Fig. 10). These maxima show that, regardless of the apogee limitation (≤1200 km), it can be confirmed that the night-time appearance of the geomagnetic anomaly is localized mainly around 1100 km. The distribution of the relative spread of the night-time maxima in ion concentration of heavy ions vs. geomagnetic latitude is shown in Fig. 11. It follows from the figure that the maximum frequency of appearance of a heavy ion concentration "ridge" is obtained to the north, in the +15 to +25° range and, to the south, in the -5 to -25° range. The altitude distribution of the maxima, relative to the total number of transits analyzed is shown in Fig. 12. These histograms, in the first approximation, permit the assertion that the greatest display of geomagnetic control in emergence of the heavy ion concentration maxima and minima (see also Fig. 10) is at an altitude of 1050-1150 km. It must be kept in mind, however, that the statistics of altitudes above 1150 km encompass a small number of cases, as a consequence of a gradual decrease in apogee of the satellite.

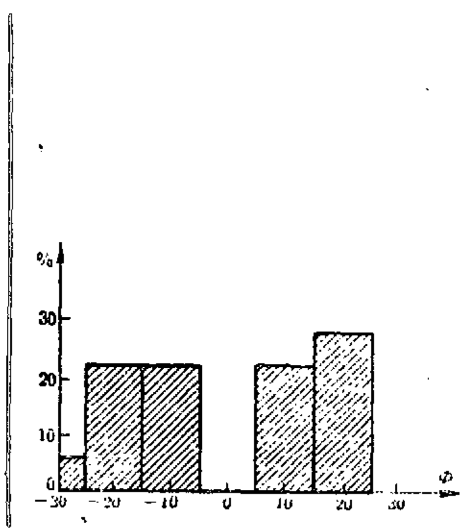


Fig. 11

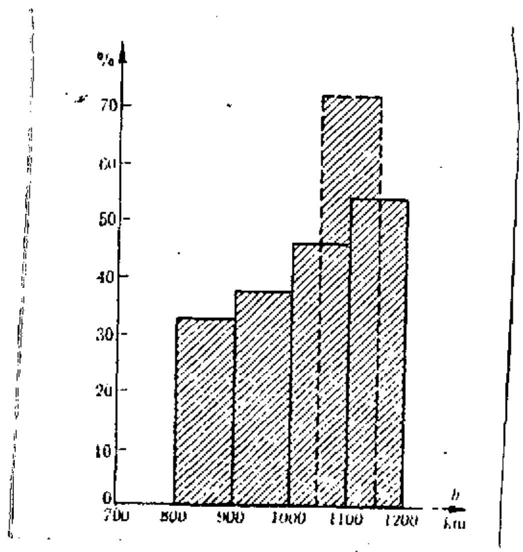


Fig. 12

The relationship of the ion concentration to the maxima and minima of the equatorial anomaly is quite variable, from a few percent to an order of magnitude. There is considerable interest in the circumstance that, in contrast to known data (see, for example, [17-19, 21]), the night-time minima around the geomagnetic equator, at altitudes above 900 km, are more sharply expressed than the average values of the depth of the daytime minima. The distances between the "ridges" of the equatorial anomaly above 900 km at night increase little with distance from local sunset. /80

No outlines of the relationship of minimum and maximum distribution in the ±30° geomagnetic latitude region to geomagnetic longitude can be established. The reason for this may be the limited amount of material analyzed, and also the relative narrowness of the range of geomagnetic longitude, in which the satellite orbit crossed the geomagnetic equator in the period being considered (from 100°E to 180° by day and from 250° to 320° by night). The geomagnetic coordinates were calculated, by means of the tables in [35, 36].

## DISCUSSION OF RESULTS AND CONCLUSIONS

The peculiarities of the satellite trajectory in the period being discussed are such that, in the illuminated part of the day, the satellite passed through the ±30° geomagnetic latitude region, at altitudes from 200 to 580 km and, at night, it passed over the same geomagnetic region at altitudes above 700 km. For this reason, the singularities of the equatorial anomaly are analyzed in this work, at relatively low altitudes by day and in the region of the apogee at night.

The results obtained here show the altitude limitation to 500 km by day of the effect on the equatorial anomaly. This is in agreement with the basic results of [17], and it shows that the proposed existence of the daytime anomaly at altitudes up to 700 km [19] is ungrounded. At least, there was a small number of passages of the satellite at altitudes above 500 km by day, and the results obtained always show the absence of the geomagnetic effect above this altitude.

The established diffuseness of the location of the maxima to the south of the geomagnetic equator and the predominance of a smaller concentration in the southern "ridge" than in the northern, apparently contradicts the series of studies [18, 37-39]. According to [39], the maximum electron (and, consequently, ion) concentration actually is better expressed on the summertime side of the magnetic equator, i.e., in our case, to the south. It is stated in [38] that a higher "ridge" is found between the magnetic equator

in the subsolar direction, which is located in the south geomagnetic latitudes in this analysis. The "diffuseness" results here in a southern position of the maximum of $n_1$ and, thus, also a predominance of higher concentrations in the northern maxima is found, in clear contradiction with a number of theories on the equatorial anomaly [19], as well as with the basis of the asymmetry in the maxima in [37], which assumes that these effects are caused by horizontal waves in the neutral atmosphere, blowing from the summer hemisphere to the winter one through the magnetic equator. Measurement data from the Alouette-1 satellite show [18] that the altitude of the constant electron concentration level is lower on the winter side of the magnetic equator, which corresponds to the northern maximum of the anomaly in our case. However, these contradictions are apparent, since the trajectory of Interkosmos-2 in the study period and the latitude range it crossed systematically /81
in the perigee region is south of the geomagnetic equator, i.e., the southern maximum formed significantly lower than the main maximum in the daily distribution of $n_1(h)$. Satellite crossings north of the magnetic equator usually were at altitudes of 215-320 km, with an average of 250 km. Analysis of the altitudes of a northern maxima of $n_1$ shows that they are found in a region closer to the main maximum in the distribution of $n_1(h)$ and, therefore, they are systematically larger than their maxima.

The solar radiation, which is superimposed on the geomagnetic control of distribution of $n_1$, has an effect on the increase in flatness of the maxima to the south, since, during the period being considered (December-January), the region south of the geomagnetic equator is at a higher altitude than the sun. The higher value of the northern maximum obtained here is in agreement with the results of [8], where it was shown that, at noon in December 1957, of the two maxima in the equatorial anomaly, the northernmost one was observed (in the Indian sector). Possibly, the results obtained in this work are affected by the higher level of the solar activity, than in the period of measurement from the Alouette-1 and Alouette-2 satellites.

Other parameters of the equatorial anomaly (location and depth of the minima, daily development of the anomaly, etc.), in practice, confirm the results of other studies [17-19, 21, etc.].

As far as is known at present, the night minimum has not been observed at altitudes over 900 km. Analysis of the data obtained have been continued, with allowance for the change in mass composition of the ions at the altitudes being considered.

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